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Ames Research Center, Dryden Flight Research Facility, Edwards, California

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DEVELOPMENT OF A TEMPERATURE-COMPENSATED HOT-FILM ANEMOMETER SYSTEM FOR BOUNDARY-LAYER TRANSITION DETECTION ON HIGH-PERFORMANCE AIRCRAFT

Harry R. Chiles and J. Blair Johnson

Ames Research Center
Dryden Flight Research Facility
National Aeronautics and Space Administration
Edwards, CA 93523

ABSTRACT

A hot-film constant-temperature anemometer (CTA) system was flight-tested and evaluated as a candidate sensor for determining boundary-layer transition on high-performance aircraft. The hot-film gage withstood an extreme flow environment characterized by shock waves and high dynamic pressures, although sensitivity to the local total temperature with the CTA indicated the need for some form of temperature compensation. A temperature-compensation scheme was developed and two CTAs were modified and flight-tested on the F-104/Flight Test Fixture (FTF) facility at a variety of Mach numbers and altitudes, ranging from 0.4 to 1.8 and 5,000 to 40,000 ft, respectively.

The temperature-compensated hot-film anemometers worked well over the Mach number and altitude range of the flight test. This paper describes the temperature-compensated hot-film anemometer and presents some of the data obtained during the flight test.

INTRODUCTION

The use of hot-film anemometers for boundary-layer transition detection is a method that has been used successfully on several low-speed aircraft (Ref. 1); however, these systems were relatively large, thus requiring a large space for instrumentation, and some systems required constant monitoring to ensure proper operation. In most cases, the instrumentation packages were mounted in benign environments such as aircraft cabins.

NASA Ames Research Center's Dryden Flight Research Facility sought to develop a hot-film anemometer system that could be used for boundary-layer analysis at transonic and low supersonic speeds. The system had to be "operator free" and compact so that it could be used on fighter aircraft. Additionally, the components had to withstand severe vibration, acceleration, and temperature and altitude changes.

The system which was developed uses hot-film anemometers for boundary-layer transition detection on high-performance fighter aircraft. This system has been designed and tested at transonic speeds.

A flight test of "hands-off," constant-temperature, hot-film anemometers on a fighter aircraft showed large sensitivity changes in the anemometer output with aircraft speed and altitude. During extremes of high speed at low altitude or low speed at high altitude, the anemometer output may saturate, resulting in a loss of flow-transition data.

An analysis of the hot-film CTA output data for both the flight test and ground testing revealed the primary cause of the sensitivity changes to be the changes in the temperature of the operating environment of the hot film. The hands-off system, using temperature compensation, was flown on the F-104 FTF facility at the Dryden Flight Research Facility.

FTF TEST AIRCRAFT

Description

The hot-film anemometer systems were flown on a specially modified F-104G aircraft, a single-engine fighter with low-aspect-ratio wings. The aircraft carries an instrumented ventral fin (Figs. 1 and 2), commonly referred to as the FTF. The F-104/FTF facility, used to conduct various local-flow aerodynamic experiments, is further described in Reference 2. For this experiment, a supercritical nose shape was mounted on the FTF.

Hot-Film Location

In order to suitably locate the hot-film gages, the results from previous flight tests that were conducted to gather pressure distributions were analyzed. Pressure distribution data obtained for a variety of Mach numbers and aircraft sideslip angles were used to determine that a natural transition on the supercritical nose shape occurred at approximately 5% chord location. Two hot-film gages were therefore placed at different span stations at 5% chord (Fig. 3).

INSTRUMENTATION

Both the aircraft and the FTF were instrumented and had their own pulse code modulation (PCM) systems. In addition, the aircraft contained a 1-in, 14-track airborne tape recorder. Standard measurements such as Mach number, altitude, total and static pressure, and angle of attack and angle of sideslip were measured on the airplane.

The FTF had its own air-data noseboom and high-accuracy total and static pressure sensors. In addition to the standard measurements, the FTF had three multiport pressure scanners (one mechanical, two electronic) for pressure measurements. Data from the aircraft and the FTF were telemetered to the ground station and were recorded on the airborne tape recorder located in the aircraft.

HOT-FILM ANEMOMETER

System Description

The hot-film CTA system consisted of two DISA Electronics hot-film gages with a nominal resistance of 10 ohms and two Thermo-Systems Inc. CTA 1750 constant-temperature anemometers. Two EGT-50A temperature-resistance gages of 50 ohms nominal resistance were added for temperature compensation. The CTA 1750 anemometer (Fig. 4) used a Wheatstone bridge circuit formed by two internal resistors, the hot-film gage, and a temperature-control resistor in series with a variable inductor. A bridge ratio of five was used to minimize self-heating of the temperature-control resistors.

The temperature-control resistor, which was mounted externally to the anemometer case, selected the hot-film operating temperature. The variable inductor provides compensation for capacitance in the wiring to the hot-film gage. The temperature-control resistor was selected for a resistance of five times the hot-film gage resistance at the selected operating temperature, plus the wiring resistance.

The anemometer amplifier circuit output provided the power to the bridge which kept the hot film at the constant resistance (therefore constant temperature) selected by the temperature control resistor, through self-heating. This same voltage was also the output of the anemometer for monitoring and/or recording. The dynamic voltage component of the anemometer output was recorded on the aircraft's airborne tape recorder, and the steady-state voltage component of the output was recorded on the FTF PCM system.

As the amount of heat carried away from the hot-film gage by the airflow changed, the output of the anemometer varied to keep the temperature constant. The output gave an indication of heat transfer. The dynamic voltage recorded on the airborne tape recorder was analyzed after the flights to determine the ability of the system to measure the flow condition at each of the test conditions. During the tests with the unmodified

CTA, the steady-state voltage level, which varies significantly with the temperature of the operating environment, was monitored to determine whether the output was normal. When temperature compensation was used, it was found that the steady-state voltage level also gave an indication of the flow condition.

The hot-film gages and the temperature-compensation gages were mounted to the surface of the FTF nose shape using double-stick cellophane tape or epoxy adhesive. The leads from the hot-film and temperature-compensation gages to the anemometers, which were mounted inside the FTF, were 22-gage shielded wires with two conductors. The wires were covered with aluminum tape at the points where they were routed outside the FTF.

Temperature-Compensation Scheme

The CTA 1750 anemometer modification (Fig. 5) consisted of the addition of two resistors and the relocation of the variable inductor. The resistors were installed so that one would be in series with the EGT-50A temperature gage, and the other resistor would be in parallel with both the first resistor and the temperature-compensation gage. One end of the hot-film gage and the temperature-compensation gage were common, with the junction being formed at the gages to allow a three-wire hookup of the two gages to the anemometer. The two gages used the two conductors of the hookup wire, with the common sides of the gages using the shield which is grounded inside the anemometer. This configuration also improved the ability of the amplifier located within the anemometer to reject unwanted noise, thus improving data quality.

The resistance values for the expected minimum and maximum operating temperatures of the hot-film and temperature-compensation gages were used to calculate the series and parallel resistor values, using the Ohms Law relationship of

$$R = [(R_t + R_s)R_p]/(R_t + R_s + R_p)$$

where R_t equals the temperature-gage resistance plus the lead-wire resistance, R_s equals the series resistor value, and R_p equals the parallel resistor value.

The resistances of the series and parallel resistors were calculated to give a total resistance for the network of the temperature gage (plus the lead-wire resistance) and the two resistors, equal to five times the resistance of the hot-film gage (plus the lead-wire resistance) at the minimum and maximum expected operating temperatures.

During flight tests, the temperature gage measures the local total temperature and the hot-film gage is heated to a temperature equal to the total temperature plus the selected operating temperature above ambient. For the flight test, the operating temperature above ambient, which was selected for the hot-film gage, was 90°C.

TEST POINTS

Several maneuvers were flown to evaluate the hot-film anemometer system characteristics. Initial flight tests were conducted to expand the hot-film flight envelope. The Mach number and altitude were increased slowly to ensure that if the hot films failed, the important parameters such as Mach, dynamic pressure, temperature, and altitude could be determined.

Once the flight envelope had been expanded, specific maneuvers were conducted. Constant Mach number and constant dynamic pressure climbs and descents were flown to establish operational characteristics of the hot-film system. The constant-Mach number descent was flown at Mach 0.8 and 0.9 from approximately 40,000 to 5,000 ft altitude. Two constant-dynamic-pressure climbs were flown — one at 300 lb/ft^2 and the other at 600 lb/ft^2.

The flights included additional test points to establish hot-film output characteristics when the laminar, transitional, and turbulent portions of the boundary layer were measured. The testing was done by flying steady-state points and then changing the aircraft sideslip (limited to 2° because of the limitations of the F-104 control system). The change in sideslip caused an effective change in the angle of attack on the FTF, which moved the transition location across the hot-film gage. Also, constant-altitude acceleration-deceleration points were flown at 30,000 and 20,000 ft, covering a Mach-number range from 0.7 to 1.8 and 0.6 to 1.6, respectively.

AERODYNAMIC RESULTS FROM A SELECTED CASE

As mentioned previously, sideslip maneuvers were flown to evaluate the ability of the hot-film anemometer system to detect transition. As the aircraft moved from 0° of sideslip to approximately 2° of sideslip (which is equivalent to an angle-of-attack change on the FTF), a diagonal transition front on the FTF moved forward, passing over hot-film 2 but remaining behind hot-film 1 (Fig. 3). The steady-state voltage was evaluated as a function of aircraft angle of sideslip (Fig. 6) for a maneuver flown at Mach 0.8 at 10,000 ft. The steady-state voltage of hot-film 1 remained constant throughout the maneuver, whereas the steady-state voltage of hot-film 2 increased from 1.8 volts to 2.2 volts as the transition location moved ahead of hot-film 2.

The dynamic voltage component of the anemometer output was also recorded for the same maneuver; a time history of the dynamic voltage component is presented in Figure 7. When the dynamic signal for transition detection was analyzed, relative changes in the signal were observed. The signal began as a small-amplitude, high-frequency signal with some large-amplitude, positive spikes. As the transition moved over the hot film, the signal increased. When the gage was in turbulent flow, the signal was much like a laminar flow signal; however, the baseline was displaced and the large-amplitude spikes were in the negative direction.

CONCLUSIONS

An operator-free hot-film anemometer system can be used for boundary-layer transition detection at transonic speeds. The system must be temperature-compensated so that the output signal level does not vary with total temperature. The sensors can survive severe aerodynamic environments, such as a shock wave passing rapidly over the gage or high dynamic pressures. The signal level does not vary the dynamic pressure.

When transition of the boundary layer is encountered, a characteristic change in the output signal is displayed by a sharp increase in amplitude and frequency of the dynamic voltage, with a corresponding change in the steady-state voltage level.
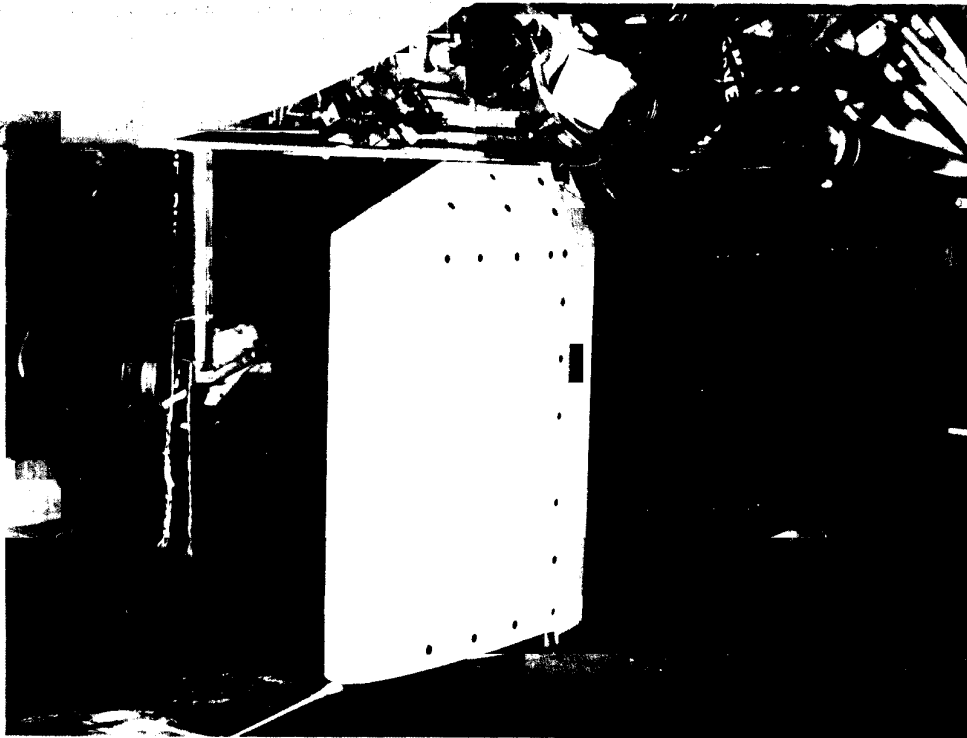
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1. Obara, C.J. and Holmes, Bruce J.: Flight-Measured Laminar Boundary-Layer Transition Phenomena Including Stability Theory Analysis, NASA TP-2417, 1985.

2. Meyer, Robert R., Jr.: A Unique Flight Test Facility: Description and Results, NASA TM-84900, 1982.
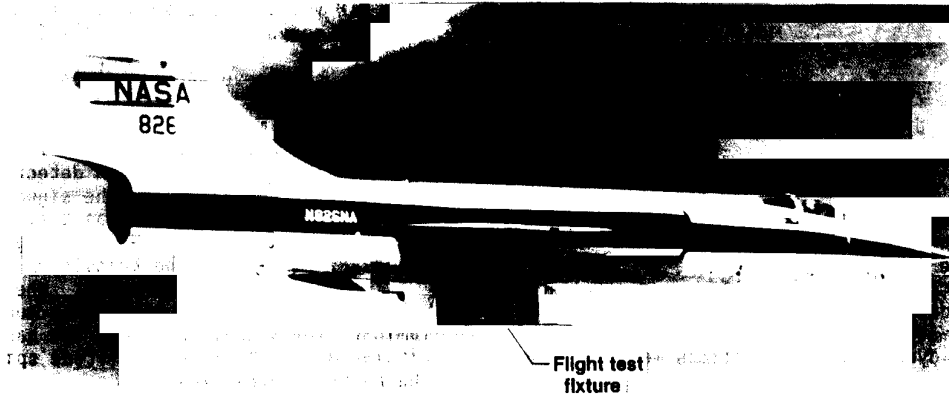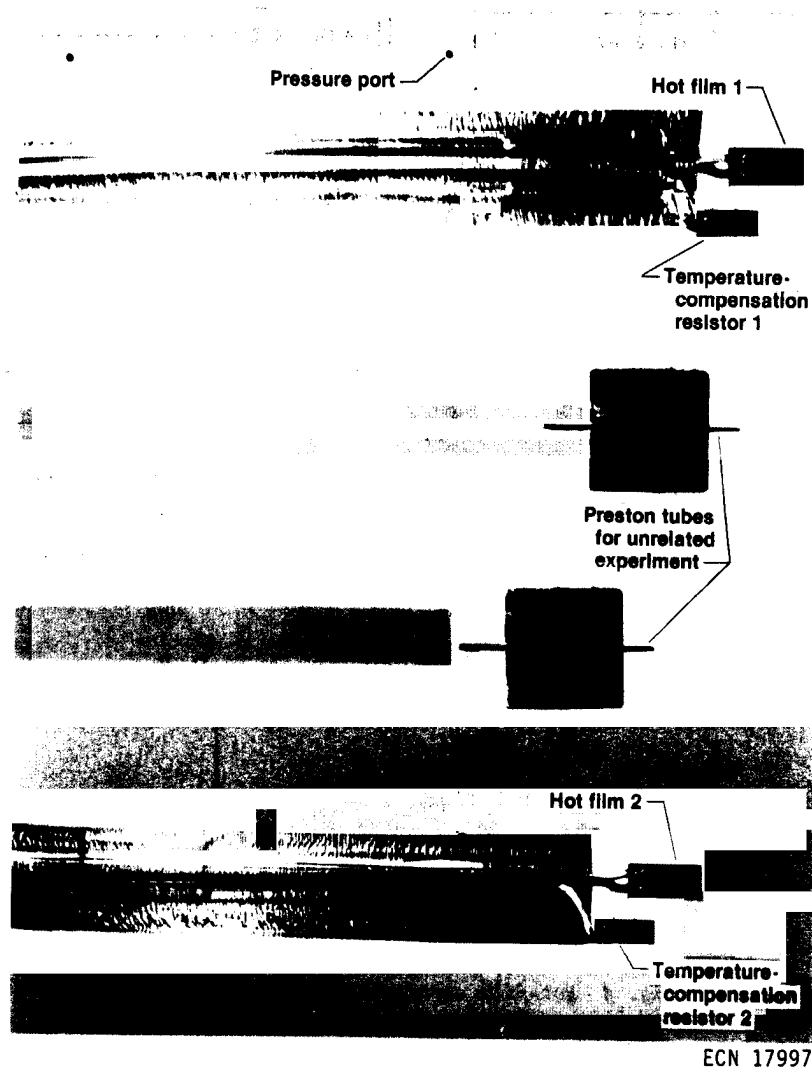
ECN 17992

Fig. 1 F-104G aircraft with flight test fixture.

ECN 31368

Fig. 2 Flight test fixture.

Pressure port — Hot film 1 —

Temperature-
compensation
resistor 1

Preston tubes
for unrelated
experiment —

Hot film 2 —

Temperature-
compensation
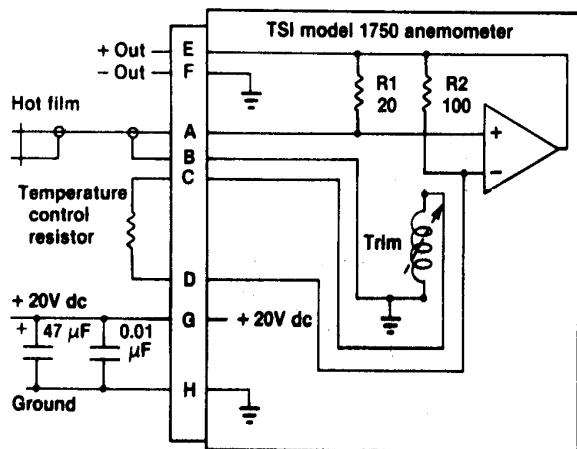resistor 2

ECN 17997

Fig. 3   Hot-film installation.

Fig. 4 Constant-temperature hot-film anemometer.
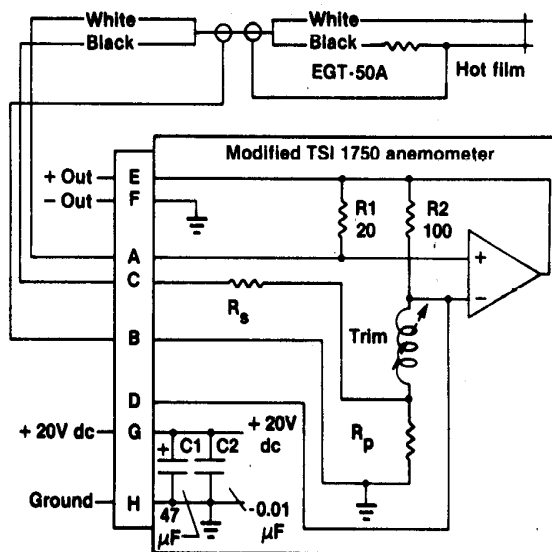
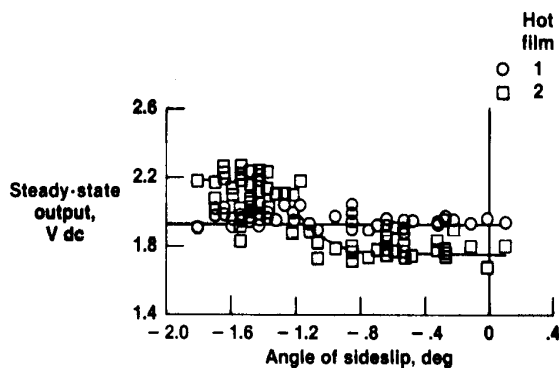Fig. 5 Temperature-compensated hot-film anemometer.

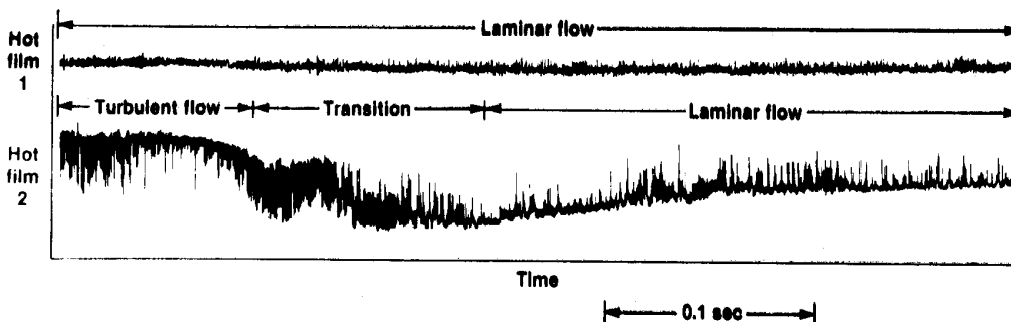Fig. 6 Hot-film steady-state output for sideslip maneuver. Mach 0.8; altitude = 10,000 ft.

Fig. 7 Hot-film dynamic output for sideslip maneuver.

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